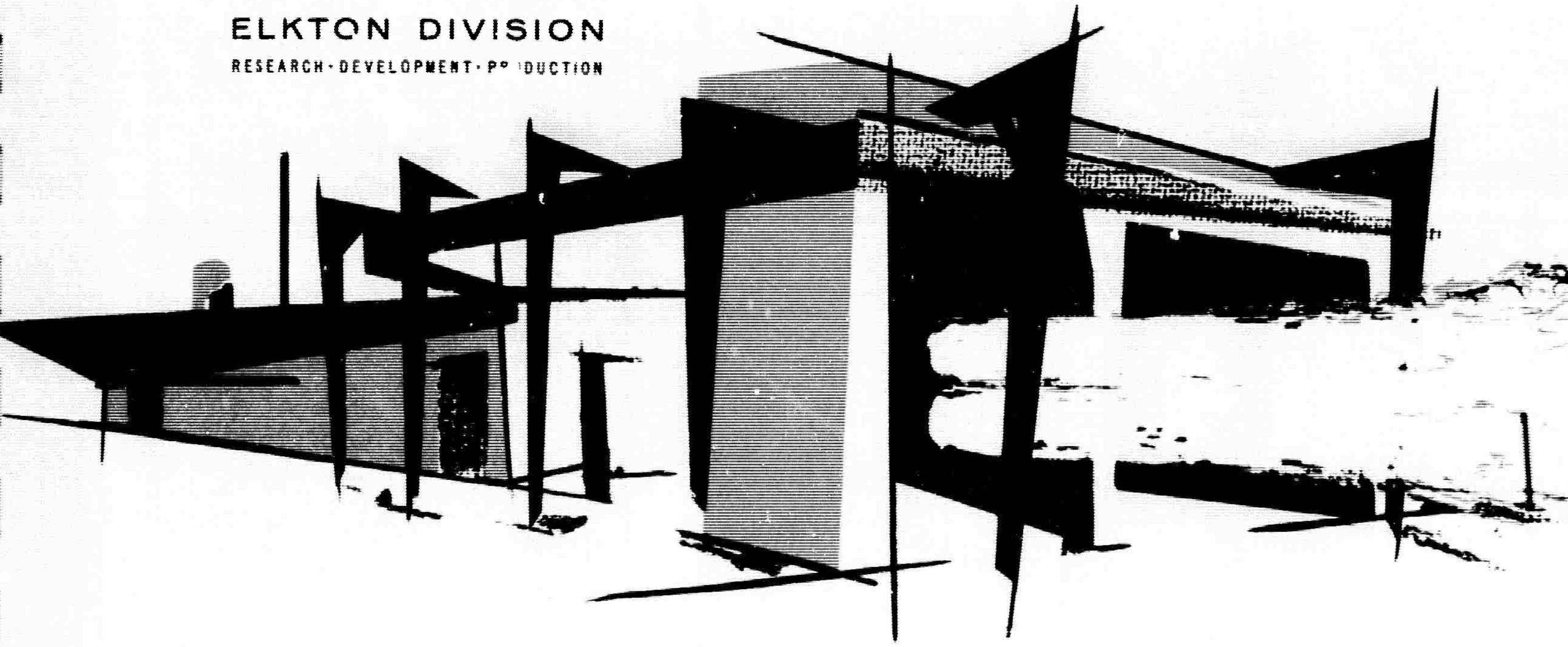
+cc E93-62
JULY 6, 1962

1

36 P

Thiokol®

ELKTON DIVISION
RESEARCH·DEVELOPMENT·PRODUCTION



QUARTERLY TECHNICAL REPORT NUMBER 4, EXPERIMENTS FOR THE MEASUREMENT OF THE ACOUSTIC IMPEDANCE OF A BURNING SOLID PROPELLANT, CONTRACT NO. NONR 3473(00)

HPC File Cy

E98-62

THIOKOL CHEMICAL CORPORATION
ELKTON DIVISION
ELKTON, MARYLAND

"EXPERIMENTS FOR THE MEASUREMENT OF THE ACOUSTIC IMPEDANCE OF A BURNING SOLID PROPELLANT"

QUARTERLY TECHNICAL REPORT NUMBER 4

FEBRUARY 15, 1962 THROUGH MAY 15, 1962

PREPARED FOR:

OFFICE OF NAVAL RESEARCH
POWER BRANCH, CODE 426
DEPARTMENT OF THE NAVY
WASHINGTON 25, D. C.

CONTRACT NO. Nonr 3473(00)
ARPA ORDER NO. 23-61, TASK 5
PROJECT CODE NO. 9100

JULY 6, 1962

H G Jones

H. G. Jones
General Manager

TABLE OF CONTENTS

FOREWORD

This quarterly report, covering the period from February 15, 1962, to May 15, 1962, has been prepared by the Elkton Division of Thiokol Chemical Corporation and describes the continuing work on Contract Nonr 3473(00), a program to develop instrumentation and to measure the acoustic impedance of a burning solid propellant.

The studies have been conducted at the Thiokol-Elkton Research Laboratories. Contributors to the program's technical work during this reporting period were: Edward S. Stern, Principal Investigator, Research Section; and Dr. Alvin O. Converse, Program Consultant, Carnegie Institute of Technology.

The studies are being conducted under the general supervision of Dr. C. C. Alfieri, Head, Research Section, and Dr. G. R. Leader, Head, Physical and Analytical Chemistry Group.

The program manager is M. David Rosenberg.

ABSTRACT

This report describes the progress of this program to measure the acoustic impedance of a burning solid propellant during the fourth quarter.

The analytical treatment to compensate for the introduction of exhaust ports in the sound chamber body is presented. Specific impedance measurements for Johns-Manville Airacoustic using various test chambers are reported. Impedance measurements at elevated pressures are discussed.

At present, passive tests have been conducted at 14.7, 500 and 1,000 psi to establish the test procedure and acceptability of the data in various modified sound chambers. The reduced data at one atmosphere confirm the acceptability of the method. Data reduction at 500 and 1,000 psi is now being performed. Propellant samples have been fired in some of these chambers to allow the measurement of pressure rise upon ignition.

A supplementary bibliography of applicable references is included as an appendix to this report.

I. INTRODUCTION

This program consists of research studies to develop instrumentation and to measure the acoustic impedance of a burning solid propellant under Contract Nonr 3473(00), ARPA Order No. 23-61. Its objective is to evaluate a modification of the method developed by O. K. Mawardi[1, 2] to measure the impedance of inert materials (passive tests). This technique will be considered feasible for this program if it can be shown that burning propellant acts as an amplifier for acoustic energy (active tests).

Working under a recent amendment to the contract, the study may now be classified in the following five parts:

(1) Continued evaluation and modification of the Mawardi-type test apparatus in order to refine techniques and to assure accuracy;

(2) Performing tests to confirm the reproducibility of the test measurements;

(3) Determining the values of impedance as a function of frequency;

(4) Characterizing a model propellant system in terms of such parameters as oxidizer particle size, burning rate, sample size; and

(5) Attempting to correlate the experimental data with theoretical concepts.

A summary of existing theoretical and experimental work upon which this study is based was presented in Quarterly Report No. 1[3]. Continuing the practice established in past quarterly reports,[4, 5] additional references that have been reviewed during the current period are presented in an appendix to this report.

II. TECHNICAL PROGRAM

The principal objective of this program is to measure the acoustic impedance of a burning solid propellant. The results that are obtained can be applied to various theoretical treatments[6, 7, 8] of solid propellant rocket instability which require knowledge of the reaction of the burning propellant surface to an acoustic disturbance. The specific acoustic impedance represents the required boundary condition.

The impedance function is determined by boundary conditions and by the point in the wave at which the impedance is designated. In the experimental technique[3, 4] being established, a loss or gain due to the reflection of the imposed sound from the burning surface will result in a change in sound intensity.

A. Phase Angle Correction

Early in this program it was tacitly assumed that the analysis requirements of a constant current through the sound driver could be justified by observing the voltage across the driver. When the input impedance of the source is large, a small change in load will not show a change in the voltage across the driver. Therefore, the volume current could be considered constant for a change in termination. Since the measured impedance of the input tube and sound source is large, the assumption that volume current is constant is justified. However, the relationship between constant driver voltage and constant volume current differs by a power factor which varies with frequency.

For a hornless moving coil driver such as the Altec speaker being used in this study, the reactance of the coil varies from a negative value through zero to a positive value, the latter due to inductance. The negative reactance at low frequencies exists by virtue of the large back e. m. f. induced in the moving coil. The reactance is zero at the electromechanical resonance frequency. Also, the greater the effective mass of the disk and coil, the lower the electromechanical resonance frequency. At frequencies above or below the resonance point, the current "lags" or "leads" on the impressed e. m. f. The further the frequency from resonance, the greater the "wattless" component of the current.

Following from this discussion, several samples were re-run. The outputs of the microphone were measured both in magnitude and phase, the phase angle being referred to the input current which was maintained constant throughout the experiment. From these tests, a phase angle correction which could be applied to the past data was obtained. The reduced data using this correction appear to show less data scatter and are more consistent than previously obtained. The magnitude of the phase correction varies from about 3 degrees at low frequencies (200 cps) to approximately 20 degrees at higher frequencies (2 Kcps).

B. Effect of Probe Tube Damping

A mismatching between the input impedance, the impedance of the tube, and the termination of the tube can cause resonance within the 4 mm I. D. probe tube. Resonance appears when a 1/4 wave length of the sound is equal to the probe tube length and again for 3/4, 5/4, 7/4 . . . wave lengths.

A smoother response has been achieved by placing damping material (fine steel wool) at the ends of the tube. The degree of damping depends mainly on the compactness of the filling. By means of a trial and error method, an "acceptable" liner characteristic response can be obtained over a wide frequency range. This is dependent on the probe tube dimensions.

Figure 1 shows the effect of adjusting the probe tube damping such that undulations on the frequency response are avoided.

C. Comments on Cavity Modifications

The basis of our treatment requires that the test method satisfies the requirements of a lumped acoustical system. This requires that the dimensions of the various elements of the acoustic system remain small in comparison with the wave length of the sound. The motion of the medium in the system is analogous to that of a mechanical system having lumped mechanical elements of mass, stiffness, and resistance. This implies that the pressure distribution inside the cavity must be constant. Mawardi[1, 2] shows, through analysis and experimental verification, that the technique used may be considered a lumped system.

Uniformity of the axial distribution of the pressure can be established by decreasing the length of the cavity. A reduction in the cavity volume (an equivalent increase in the impedance of the cavity) also improves the behavior of the detector. Operation of the source as an infinite input impedance, however, is enhanced by large volumes at the low frequencies. As the frequency is increased, the cavity volume is made smaller so that the uniformity of pressure distribution does not suffer.

Impedance measurements on passive materials are conducted in a solid cavity having essentially no dissipation at the walls. At the rigid boundary, there can be no

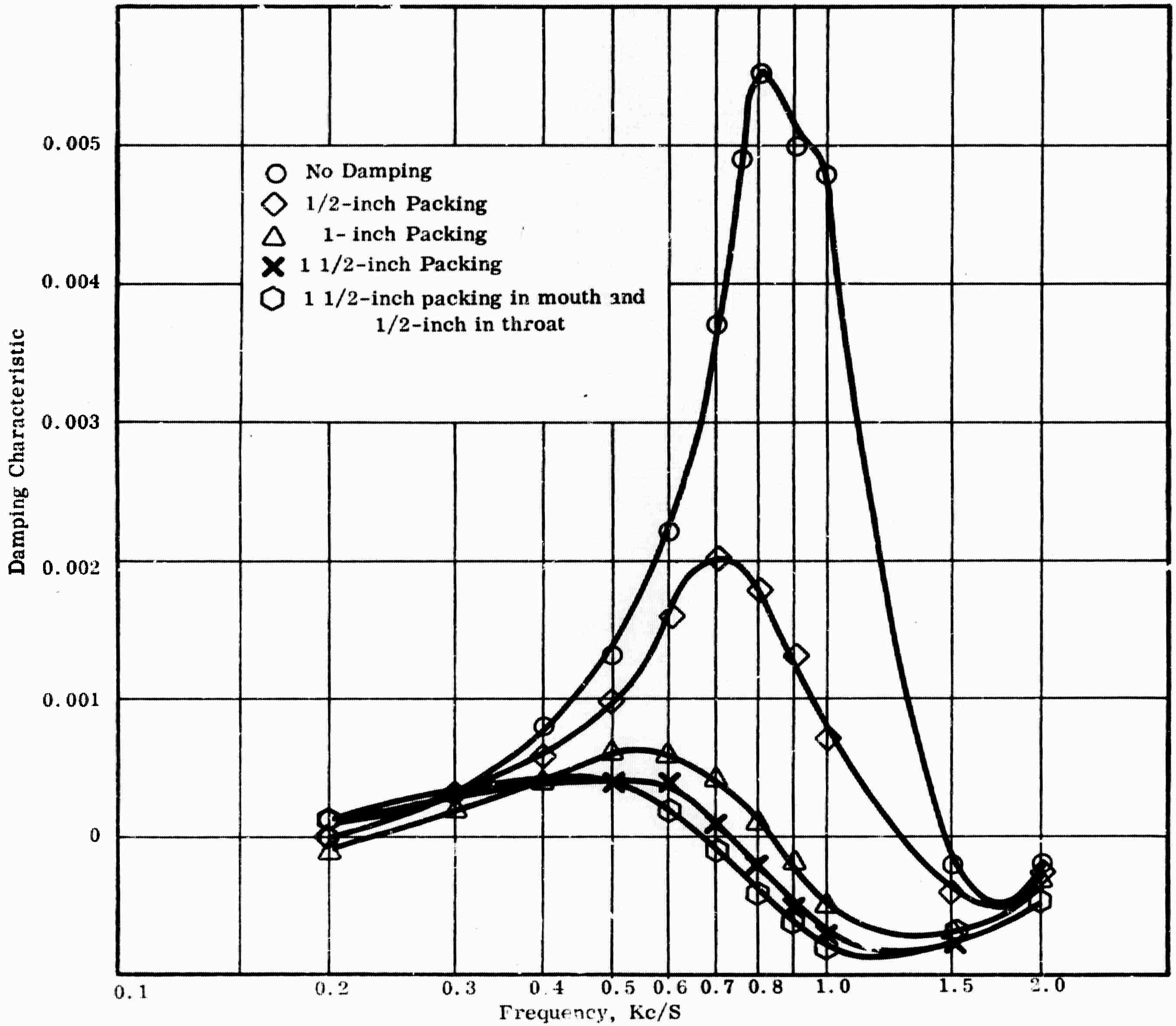


FIGURE 1. EFFECT OF PROBE TUBE DAMPING ON FREQUENCY RESPONSE OF MICROPHONE

particle velocity normal to the boundary. The impedance is purely reactive at all distances from a perfectly rigid boundary. The impedance can run through all values from $-\infty j$ to $+\infty j$ if the cavity length is increased by a half wave length. Within a quarter wave length of the rigid termination, the impedance is negative reactance, which corresponds to a capacitive reactance in an electric circuit and to a stiffness in a mechanical circuit. Right at the boundary, the sound wave feels an infinite stiffness. In such a chamber, the acoustic impedance is an inertial reactance, analogous to electric inductive reactance. Ideally, such a chamber would not drain energy from a source, and the smallest amount of sound would continue forever. It is then possible to write that the chamber impedance $Z_c = -jX$. The reactance, X, of the cavity can be expressed by $-\gamma Pj/2\pi fV$. The impedance is not independent of frequency because of the transition from isothermal expansions of the air at low frequencies to adiabatic expansions of the air at high frequencies within the cavity as frequency is altered.

Since the solid cavities have no dissipation, their behavior is physically analogous; therefore, the ratio of their impedance is a real number, which is the ratio of geometrical similitude.

The phase angle of the impedance is identical to the phase angle between pressure and density. This phase lag between pressure and density is a function of frequency. Therefore, the energy dissipated per unit volume and per cycle is proportional to the product of energy density and absorption per wave length.

Modifications to the solid wall cavity may cause the chamber impedance to be comprised of a real and imaginary component. The real or resistive part relates to the work which is dissipated during one cycle; the imaginary or reactive part relates to the amount of energy which is stored and given back to the system in one period.

The introduction of exhaust ports to allow mass flow during the active tests comprises such a modification. At the opening, there is radiation of sound into the surrounding medium, which leads to the dissipation of acoustic energy and thus provides the resistance element.

Using dissipationless cavities, two measurements are made with two different loads, Z_1 and Z_2, recording the corresponding values of $(E_1/I)_1$ and $(E_1/I)_2$, and represented by M_1 and M_2 where M_1 and M_2 are complex quantities and I is the volume current. With the current to the sound driver always adjusted to the same value, the ratio M_1/M_2 will be the ratio of the pressures or, what is equivalent, the ratio of the output voltages of the microphone amplifier.

If the two cavities are so chosen that $|M_1/M_2| > 1$, then this requires that $|Z_1/Z_2|$ also be greater than unity.

It follows that

$$M_1/M_2 = \rho e^{j\phi} \qquad \rho e^{j\phi} \sim \frac{Z_1}{Z_2}$$

Let $Z_1 = a + bj$ be a cavity with exhaust ports and

$Z_2 = c + dj$ be a solid walled cavity

then $c = o$

and $a = -d\rho \sin \phi$ and $b = d\rho \cos \phi$.

By this technique it is possible to determine the resistive and reactive contributions to the chamber impedance of the cavity by the introduction of the exhaust ports.

The sound chamber with exhaust ports may also be considered as a Helmholtz resonator since such a resonator consists of a rigid wall enclosure communicating with the external medium through a small opening.

Expanding this approach, the chamber can be treated as being composed of a cavity with several orifice side branches. The branch impedance of such an orifice has both a real and imaginary part. The real term results from that portion of the generated plane wave which issues radiation of sound through the ports into the external medium. In this case there is no returning wave. The specific acoustic impedance of this part is a pure resistance. The imaginary term results from the inertance characteristic of the gas in the orifice. As the radius of the orifice is increased, the attenuation of the low frequencies is increased. In treating the ports as several orifices located near enough to one another so that they may be considered a single point (separated by a small fraction of a wave length), the over-all effect of the group is that of their equivalent parallel impedance.

D. Applicability of the Method

The surface acoustic impedance is a concept that applies only to a linear system, at least as used in this work. The system can be considered linear if and only if the oscillations have a sufficiently small amplitude.

One exception to the above may exist because the volume of the chamber, $V(t)$, is increasing with time; there are terms such as $V(t)\tilde{p}(t)$, which do not go to zero as quickly as the other non-linear terms, e.g., $\tilde{\mu}(t)\tilde{p}(t)$, when the amplitudes of the oscillating components are made small. The superscript $\sim$ indicates terms which oscillate with time. Notice that the component of V(t) of concern here does not oscillate. $\tilde{p}$ is the oscillating component of the pressure and $\tilde{\mu}$, the oscillating component of the velocity. In the experiments to be run in the immediate future, this effect will be neglected on the basis that $\frac{dV(t)}{dt}$ is much smaller than the corresponding oscillations. If this assumption is not valid, then it may be necessary to support the propellant on an elevator so as to maintain constant chamber volume.

An additional consideration in the treatment of the data from active firings will involve the absorption and velocity dispersion; i.e., as treated in a first-order theory of elastic waves in fluids.

From a microscopic point of view, the following three factors may be expected to produce a time lag between pressure and density in a sound wave: viscosity; heat conduction; and heat radiation. If the excess pressure and excess density in a sound wave are in phase, no absorption occurs. In gases, viscosity and heat conduction come into play about equally, but they are often overshadowed by molecular phenomena. The effect of these factors will also be considered further in the analysis of the data from the active tests.

E. Comparison of Reported Data

Discussions in Quarterly Report 3[5] reflected the difficulties in obtaining an appropriate understanding of the precision of corresponding impedance measurements as reported in the literature. To clarify these discussions, Table I shows a comparison of reported data on Celotex C-4. The technique of both investigators made use of a "rigid wall backing" of the sample.

Table II is an example of raw data obtained in our tests. The sample is first tested with increasing frequency; then the test is repeated with the decreasing frequency throughout the range under study.

Analysis of the data obtained by this treatment shows a decrease of the resulting reduced data scatter as later shown in Table III, Specific Impedance of Johns-Manville Airocoustic.

TABLE I

COMPARISON OF REPORTED DATA ON JOHNS MANVILLE CELOTEX C-4

f, Kcps	(1) R/ρ c	(2) X/ρc	(3) R/ρc	(4) X/ρc
0.02	3	-64.1	--	--
0.04	2.5	-19.5	--	--
0.06	3.4	-11.5	--	--
0.10	2.9	- 5.85	3	-16
0.20	2.2	- 5.0	3	-8
0.40	1.95	- 1.1	3	-3.5
0.60	2.75	- 0.2	3	-1.0
0.80	3.60	1.42	3	1.0
1.0	4.95	1.75	3	2.5
2.0	7.05	2.80	5	5
3.0	7.60	1.84	9.5	4
4.0	3.14	- 6.24	10	0.2

Note: Columns (1) and (2) - Mawardi, O. K., N5ORI-76 Project Order X, NR-014-903

Columns (3) and (4) - Beranek, L. L., J. Ac. Soc. Am., 12, 14, July 1940

TABLE II

TYPICAL RAW DATA TAKEN ON A RIGID TERMINATION IN A SOLID CHAMBER OF LENGTH 1.52 cm INDICATING REPRODUCIBILITY ACHIEVED

f, Kcps	Frequency Increasing			Frequency Decreasing		
	Vmic	ø	Sense, ø	Vmic	ø	Sense, ø
0.2	0.120	147	-	0.120	147	-
0.3	0.089	175	+	0.089	175	+
0.4	0.077	138	+	0.077	138	+
0.5	0.073	97	+	0.073	96	+
0.6	0.072	52	+	0.073	52	+
0.7	0.075	6	+	0.075	6	+
0.8	0.081	38	-	0.080	37	-
0.9	0.100	103	-	0.100	101	-
1.0	0.090	171	+	0.089	173	+
1.5	0.0061	39	-	0.0061	38	-
2.0	0.004	166	-	0.004	166	-

F. Treatment of Data

The impedance of the sample material is given by:

$$Z_x = Z_c \left(1/\mathcal{F} e^{j\phi} - 1 \right) \left(\frac{1}{1 + \frac{Z_c}{Z_o}} \right)$$

Referring the specific impedance of the material to ρc units,

$$\frac{Z_x \cdot A}{\rho c} = \frac{Z_c \cdot A}{\rho c} \left(\frac{1}{\mathcal{F} e^{j\phi} - 1} \right) \left(\frac{1}{1 + \frac{Z_c}{Z_o}} \right)$$

The last term appears as a correction coefficient and can be incorporated in:

$$Z_c' = \frac{Z_c}{1 + Z_c/Z_o}$$

The general formula for the impedance is then:

$$Z_x = Z_c' \left(\frac{1}{\mathcal{F} e^{j\phi} - 1} \right)$$

At one atmosphere, the correction term is mainly needed for very low frequencies, such as those in the 200 to 2000 range now under evaluation.

When dealing with closed cavity measurements, it is convenient to express the acoustical input impedance in terms of the acoustical impedance of an equivalent volume, $Z_c = -\gamma P j / 2\pi f V$. For sound bodies which have exhaust ports, the chamber impedance is $Z_c = a + bj$, where a and b are determined from the procedure just described. The real and imaginary parts of the specific impedance are calculated from the following:

$$R/\rho c \;=\; a\left[\frac{\xi\cos\phi\;-1}{\xi^{2}+1-2\xi\cos\phi}\right]+bj\left[\frac{-\xi\; j\sin\phi}{\xi^{2}+1\;-2\xi\cos\phi}\right]$$

$$X/\rho c \;=\; a\left[\frac{-\xi j\;\sin\phi}{\xi^{2}+1-2\xi\cos\phi}\right]+bj\left[\frac{\xi\cos\phi-1}{\xi^{2}+1-2\xi\cos\phi}\right]$$

In Table III, the results of measurements at atmospheric pressure using chambers with different volumes and port sizes are compared.

As the frequency is increased, the volume of the cavity should be made smaller so that the uniformity of the pressure distribution will not suffer. The 60 cm^3 volume cavity, with a cavity length of 4.56 cm, was originally designed to operate in the range of 10 to 200 cps. Although the use of this larger chamber would keep ignition pressure rise problems to a minimum, the data indicate a breakdown in the required uniformity of the pressure distribution.

TABLE III

SPECIFIC IMPEDANCE OF JOHNS MANVILLE AIRACOUSTIC USING DIFFERENT CHAMBERS

Cavity Volume, cm^3	20	60	20	20	20	20	60
No. ports	--	--	4	8	4	8	4
Port Size, in	--	--	1/16	1/16	1/8	1/8	1/16
Total Area, in^2	--	--	0.0123	0.0246	0.0492	0.0984	0.0123
Pressure	1 atm	1 atm	1 atm	1 atm	1 atm	1 atm	1 atm
f, Kcps	R/ρc	R/ρc	R/ρc	R/ρc	R/ρc	R/ρc	R/ρc
0.2	1.70	2.31	1.34	0.84	2.00	4.07	3.95
0.3	2.13	1.84	1.75	2.35	2.37	1.86	2.74
0.4	2.77	2.89	2.07	4.61	2.51	1.14	3.15
0.5	2.58	2.13	2.23	2.82	2.36	2.47	2.96
0.6	2.31	2.10	2.12	3.08	2.52	3.69	2.85
0.7	2.57	2.10	2.23	2.64	2.61	2.88	2.25
0.8	1.91	1.92	2.16	2.20	1.79	2.17	1.21
0.9	2.44	1.59	1.61	2.45	2.35	2.33	2.05
1.0	2.46	1.45	1.34	2.47	2.37	2.71	1.78
1.5	2.29	2.00	1.57	2.51	2.30	2.44	0.13
2.0	1.54	2.71	3.38	4.11	2.21	2.53	-0.25
	X/ρc	X/ρc	X/ρc	X/ρc	X/ρc	X/ρc	X/ρc
0.2	-10.6	-13.9	-12.9	-14.4	-15.8	-15.1	-5.1
0.3	- 8.1	-10.1	- 8.5	- 9.2	-10.5	- 9.2	-9.1
0.4	- 6.4	- 7.0	- 6.5	- 6.1	- 6.8	- 8.0	-6.8
0.5	- 5.4	- 4.6	- 4.7	- 5.3	- 5.9	- 5.1	-4.7
0.6	- 4.1	- 3.3	- 4.0	- 4.1	- 4.3	- 3.8	-3.5
0.7	- 3.4	- 2.3	- 3.4	- 3.4	- 3.5	- 4.3	-2.7
0.8	- 3.7	- 1.8	- 3.5	- 2.4	- 3.6	- 3.4	-2.0
0.9	- 2.4	- 1.4	- 2.7	- 2.5	- 2.5	- 2.5	-0.99
1.0	- 2.1	- 0.88	- 1.7	- 2.2	- 2.2	- 2.2	-0.43
1.5	- 1.1	+ 1.6	- 1.1	- 1.7	- 1.6	- 1.8	+0.84
2.0	- 0.9	+ 0.59	- 1.6	- 1.1	+ 0.57	- 0.2	+0.38

G. Measurement of Acoustical Materials at Elevated Pressures

The acoustic properties of a homogeneous, isotropic material are fully characterized when the propagation constant and characteristic impedance are known. These quantities are derived from the physical properties of the material. The properties evolved are: specific flow resistance; porosity; structure factor; volume coefficient of elasticity of the air in the interstices; and volume coefficient of elasticity of the skeleton of the material.

The propagation constant b is composed of a real and an imaginary part; the attenuation constant and the phase angle, respectively. It is related to the physical properties of the acoustical material depending on the nature of the acoustical material. When the volume coefficient of elasticity of the air in the interstices is greater than 20 times that of the skeleton, the propagation constant, b, is given by:

$$\text{(1)} \qquad b = j\omega \sqrt{\frac{\rho_o k Y}{K}} \sqrt{\frac{(R_1/\rho_m\omega)^2 \; (Y + \rho_m/\rho_o k \;\; + 1 - j\,(R1/\rho_m\omega)\cdot(\rho_m/\rho_o k)}{1 + (R_1/\rho_m\omega)^2}}$$

When the material is more rigid, as in the case of Johns-Manville Airacoustic, then

$$\text{(2)} \qquad b = j\omega \sqrt{\frac{\rho_o k Y}{K}} \sqrt{1 - j\,\frac{R_1}{\rho_o k\omega}}$$

The characteristic impedance Z_o' is calculated from

$$\text{(3)} \qquad Z_o' = \frac{-jKb}{\omega Y},$$

The normal specific acoustic impedance, Z_n, for a sample material of thickness d with rigid wall backing is:

$$\text{(4)} \qquad Z_n = Z_o' \coth bd$$

An important term in these equations is the volume coefficient of elasticity, K. For isothermal conditions, $K = P = 10^6$ dynes/cm^2 under normal atmospheric conditions. For adiabatic conditions, $K = \gamma P \doteq 1.4 \times 10^6$ dynes/cm^2. At some frequencies in fibrous acoustical materials, K will be neither adiabatic nor isothermal and will be complex. The porosity of a sample, the structure factor or the volume coefficient of elasticity of the skeleton of the material would not be expected to vary as greatly as K under pressure. It is seen from equation (3) that pressures of 500 psi and 1,000 psi would increase the magnitude of Z_0' by 34 and 68 times, respectively.

Porous materials produce attenuation partly by acting as a reflecting surface and partly by viscous losses in the interstices. The action of acoustical materials at elevated pressures should behave more as a true rigid termination.

It is of interest to investigate the impedance as a function of pressure and frequency. The behavior of the real part of the specific impedance might well be represented as shown in Figure 2.

A series of additional passive measurements will be made at various pressures to substantiate this hypothesis.

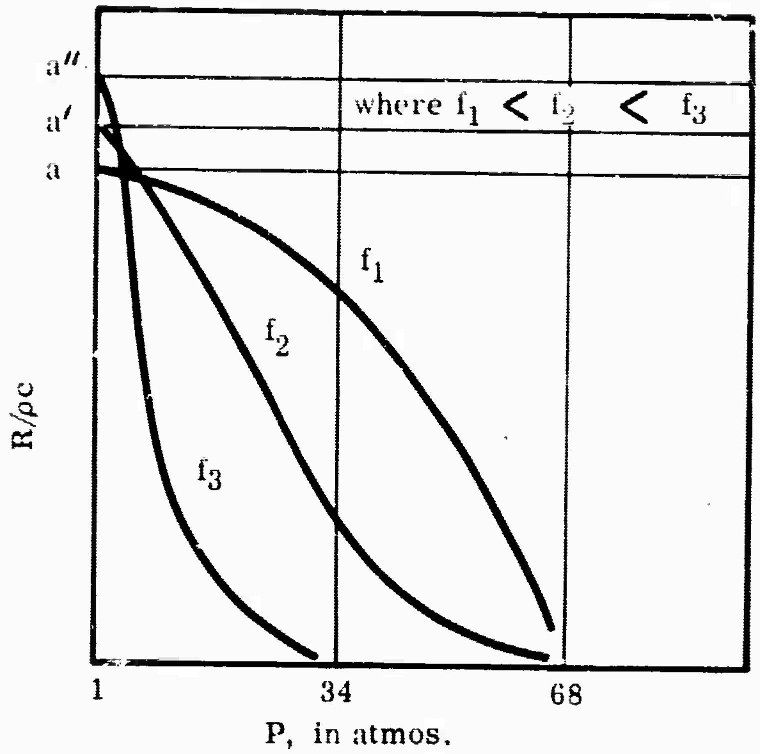


FIGURE 2.

III. SUMMARY

The basic standardization experiments on the passive system are complete. All the necessary data at 14.7, 500 and 1,000 psi, using sound chambers with various port sizes and total port areas, have been collected. The reduced data at one atmosphere confirms the acceptability of the present instrumentation and the analytical treatment of the data being used. Calculations on data taken at 500 and 1,000 psi are presently being performed.

IV. FUTURE WORK

During the next quarterly period, work will be devoted to resolving the difficulties in reducing the pressure impedance data and substantiating the action of acoustical materials at elevated pressures. More intensified work will be applied to the problem of pressure rise on ignition and additional active testing.

V. NOMENCLATURE

A = area of specimen, cm^2

a = impedance equation constant

b = propagation constant, nepers/cm; also impedance equation constant

c = impedance equation constant

d = thickness of sample, cm; also impedance equation constant

f = frequency

j = $-\sqrt{-1}$

k = structure factor

K = Volume coefficient of elasticity of air, $dynes/cm^2$

L = length of cavity

P = atmospheric pressure

R_1 = dynamic specific resistance per centimeter, rayls/cm

V = volume of cavity

X = reactance

Y = porosity, ratio of volume of voids to its total volume

Z_o' = characteristic impedance, rayls

Z_o = parallel combination of input impedances of source and detector

Z_c = impedance of cavity

Z_x = unknown impedance to be measured

Z_n = normal specific acoustic impedance, rayls

ω = $2\pi f$, cycles

γ = ratio of specific heats

ρo = density of air, gm/cm^3

ρm = density of acoustical material, gm/cm^3

ρc = characteristic impedance of a plane wave

ζ = ratio of microphone voltages

ϕ = phase angle

VI. REFERENCES

1. Mawardi, O. K., "Measurement of Acoustic Impedance," J. Ac. Soc. Am., pp 84-91, March 21, 1949.

2. Mawardi, O. K., "Measurement of Acoustic Impedance," ONR Tech. Memo b, NR-014-903, May 25, 1949.

3. Thiokol Chemical Corporation, Elkton Division, "Experiments for the Measurement of the Acoustic Impedance of Burning Solid Propellant," Quarterly Report No. 1, E149-61, May 15 - August 15, 1961.

4. Ibid, Quarterly Report No. 2, E194-61, August 15 - November 15, 1961.

5. Ibid, Quarterly Report No. 3, E47-62, Nov. 15, 1961 - February 15, 1962.

6. McClure, F. T., Hart, R. W., and Bird, J. F., "Solid Propellant Rocket Motors as Acoustic Oscillators," Progress in Astronautics and Rocketry, 1, 295-358 (1960).

7. McClure, F. T., Hart, R. W., and Bird, J. F., "Acoustic Resonance in Solid Propellant Rockets," J. Appl. Phys., 30, 1501-1514 (1959).

8. Hart, R. W., and McClure, F. T., "Combustion Instability: Acoustic Interaction with a Burning Surface," J. Chem. Phys., 30, 1501-1514 (1959).

APPENDIX

SUPPLEMENTARY BIBLIOGRAPHY

APPENDIX

SUPPLEMENTARY BIBLIOGRAPHY

Additional references allied to this study which have not appeared in the bibliography of previous quarterly reports are summarized here.

References from the open literature are listed by senior author, while references from other sources are listed by institutional affiliation.

1. AeroChem Research Lab., Inc., "Acoustic Wave Burning Zone Interaction in Solid Propellants," Quarterly Progress Report No. 3, January 1, 1962 - March 31, 1962, Contract Nonr 3477(00), ARPA Order No. 23-61 (U)

Reported is the frequency spectrum of the combustion noise from burning strands of solid propellant. For the propellant tested, both double base and composite, the sound intensity increased sharply from 1000 cps to a maximum at approximately 3000 cps and then decreased monotonically with frequency beyond 3000 cps. The oxidizer particle size changed the sound intensity level of the spectrum curve, but not its form.

2. Aerojet-General Corp., "High Frequency Combustion Instability," R. G. Peoples and P. O. Baker, L. S. Knowles, Rpt 2126, Nov. 1961, Contract AF49(638) 178 (U).

Analytical and experimental studies of stable and unstable combustion phenomena were conducted to determine the parameters affecting inherent stability. Inherent stability is determined by the amount of pressure sensitive energy available to a given pressure perturbation.

3. Aerojet-General Corporation,"Quarterly Progress Report on Unstable Burning Research Program," November 1, 1961 - January 31, 1962, April 24, 1962, Lockheed Purchase Order No. 18-02211 (U).

A program using a 6-inch side venting burner was developed by E. W. Price of NOTS to study unstable burning of composite propellants in the following areas: effect of oxidizer and aluminum particle size on the suppression of high frequency instability; stability of deflagration of ammonium perchlorate; low frequency instability studies; and catalysis of gas-phase reactions.

4. Aeronautical Research Council, (U. K.), "A Theory of Resonant Burning of Solid Propellants Assuming a Constant Surface Temperature," A. G. Smith, A. R. C. -21, 018, May 12, 1959 (U).

The theory assumes that the solid propellant becomes gaseous immediately upon reaching a fixed temperature. Results of this theory are:

a) At low frequencies, burning rate is in phase with pressure.

b) At high frequencies, burning rate leads the oscillatory pressure.

c) Response to a step function of pressure is an overshoot of burning rate.

d) At high frequencies, the burning rate amplitude to pressure amplitude ratio is greater than at low frequencies; the ratio is proportional to the square root of the frequency, and is independent of the steady burning rate.

5. Aeronutronic, "Study of Resonance Behavior in Solid Propellants," First Quarterly Report, Pub. No. C-1630, April 15, 1962, H. Shoenfield, Y. H. Inami, J. Killian, Contract NOw 62-0503-C, Task No. 2 (C).

Observations are reported on the inherent combustion pulsations of aluminized propellants. Results of exploratory experiments lend support to the idea of associating radiation output from a perturbed burning propellant with instantaneous burning rate.

6. Applied Physics Laboratory, The Johns Hopkins University, "Acoustic Attenuation in a Solid Propellant," B. H. Noll, TG-335-10, April 1962 (U).

The acoustic attenuation in rods of double base propellant (1-inch diameter x 15-inches) has been measured for longitudinal excitation. The velocity of sound in the rod was found to be a sensitive decreasing function of the temperature.

7. Applied Physics Laboratory, Johns Hopkins University, "Quarterly Review of APL Activities, October - December 1961, II, Space Exploration and Research and Development," (C), Bumblebee Report No. 309B, p. 69 (U).

This report briefly summarizes acoustic studies of propellants at the Research Center.

8. Jet Propulsion Laboratory, "Sound Radiation from a Turbulent Boundary Layer," G. J. Laufer, Tech. Rpt. No. 32-119 (U).

The phenomenon of energy radiation as sound from a turbulent zone arises on removing the restriction of uncompressibility. For the turbulent boundary layer case, indications are that the intensity of radiation becomes significant only in supersonic flows.

9a. Princeton University, "Research on Solid Propellant Instability," R. H. Waesche, K. P. Hall, Aeronautical Eng. Rpt. 564-a, August 3, 1961, Contract AF49(638)1073(U).

9b. Princeton University, "Research on Solid Propellant Instability," R. H. Waesche, J. Wenograil, Aeronautical Eng. Rpt. 564-b, Dec. 20, 1961.

This is a research program directed to the study of non-steady combustion of solid propellants with application to rocket instability.

A film strip of a metallized solid propellant burning in an oscillating pressure field was analyzed to determine the phase relationship between the imposed pressure maximum and an apparent wave of luminosity in the combustion gases. Implications of these observations are discussed.

10. Procedyne Associates, "The Use of Signal Analysis Techniques in the Analysis of Solid Propellant Viscoelastic Behavior," E. I. Henley, K. Staffin and R. Staffin (U).

An example of applying a technique by which a mathematical characterization of a system can be achieved by analyzing its response to an upset is presented.

11. Purdue University, Jet Propulsion Center, "Investigation of Velocity Upon Burning Rate of Solid Propellants; First Quarterly Report," J. M. Murphy, Report I-61-3, December 1961, Contract AF-04(611)-7445.

A critical review partially completed of the literature concerned with the erosive burning of solid propellants is presented.

12. Rocket Propulsion Establishment - Westcott (U.K.), "Review of Experimental Research on Unstable Burning in Solid Propellant Rocket Motors," March 1961, J. Diedericksen, Tech. Memo. 220 (C).

The paper describes experimental techniques used to study the mechanism of unstable burning and to find solutions to specific cases of the problem.

13. Stanford Research Institute, "Abstracts of Papers: Joint Meeting of AFOSR Contractors in Solid Rocket Combustion and the Panel on Solid Propellant Combustion Instability," SRI Project 2770, AFOSR 2348, April 1962 (U).

14. Arden, E. A., Powling, J., and Smith, W. A. W., "Observations on the Burning of Ammonium Perchlorate," Combustion and Flame, 6, March 1962 (U).

At pressures below self sustaining deflagration, combustion was maintained by minor fuel additions. The chemical nature of the added fuel is immaterial; volatility has some effect on the burning rate/flame temperature relationship. For relatively nonvolatile fuels, unusual modes of flame reaction occur within the surface.

15. Dickinson, L. A., "Command Initiation of Finite Wave Axial Combustion Instability in Solid Propellant Rocket Engines," ARS J. 32, No. 4, April 1962 (U).

The technique consists of disturbing the gas flow field by firing a charge at preselected intervals during engine operation to verify the absence of incipient instability.

16. Horton, M. D., "Acoustic Admittance of a Burning Solid Propellant Surface," *ARS J. 32,* No. 4, April 1962 (U).

Firings were made in burners of various lengths and the admittance was determined as a function of frequency. Experimental plots of the real part and the imaginary part of the admittance are given.

17. McClure, F. T., "Rockets, Resonance, and Physical Chemistry," *Science, 35,* 771-776, March 9, 1962 (U).

This paper is based on the author's address to the Washington Chemical Society on the occasion of his accepting the Hildebrand prize.

DISTRIBUTION

Office of Naval Research
Power Branch (Code 426)
Department of the Navy
Washington 25, D. C.
Attn: Dr. Ralph Roberts
(2 copies)

Director, Advanced Research Projects Agency
The Pentagon
Washington 25, D. C.
Attn: Technical Information Officer
(6 copies)

Solid Propellant Information Agency
Applied Physics Laboratory
Johns Hopkins University
8621 Georgia Avenue
Silver Spring, Maryland
(3 copies)

Dr. F. T. McClure
Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland

Dr. I. Silver
Department of the Navy
Bureau of Naval Weapons (RMMP-11)
Washington 25, D. C.

Special Projects Office
Department of the Navy
Washington 25, D. C.
Attn: LCDR R. L. Mcarthy

Naval Research Laboratory
Washington 25, D. C.
Attn: Dr. M. W. Oleson

Naval Ordnance Test Station
China Lake, California
Attn: Mr. E. W. Price

National Aeronautics and Space Admin.
1520 H Street
Washington 25, D. C.
Attn: Mr. E. Mitchell

National Aeronautics and Space Admin.
1520 H Street
Washington 25, D. C.
Attn: Mr. W. Cohen

Office of Aerospace Research
Department of the Air Force
Washington 25, D. C.
Attn: Mr. J. F. Masi

Ballistic Research Laboratories
Aberdeen Proving Ground
Maryland
Attn: Dr. L. A. Watermeier

Ballistic Research Laboratories
Aberdeen Proving Ground
Attn: Dr. J. H. Frazer

Allegany Ballistics Laboratory
Hercules Powder Company
Cumberland, Maryland
Attn: Mr. T. A. Angelus

Polytechnic Institute of Brooklyn
333 Jay Street
Brooklyn, New York
Attn: Professor R. D. Agosta

United Technology Corporation
P. O. Box 358
Sunnyvale, California
Attn: Dr. D. Altman

Grand Central Rocket Company
P. O. Box 111
Redlands, California
Attn: Dr. A. T. Camp

Office of Chief of Ordnance
Research and Development
Department of the Army
Washington 25, D. C.
Attn: Mr. J. A. Chalmers

Aerojet-General Corporation
Azusa, California
Attn: Dr. R. L. Lou

Aerojet-General Corporation
Azusa, California
Attn: Mr. R. F. Chaiken

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor S. I. Cheng

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor L. Crocco

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor M. Summerfield

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor J. Fenn

Harvard University
Department of Mechanical Engineering
Cambridge, Massachusetts
Attn: Professor H. W. Emmons

Chesapeake Instrument Company
Shadyside, Maryland
Attn: Mr. J. W. Fitzgerald

Atlantic Research Corporation
Alexandria, Virginia
Attn: Dr. R. Friedman

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena 3, California
Attn: Dr. E. M. Landsbaum

Quantum Dynamics
19458 Ventura Boulevard
Tarzana, California
Attn: Dr. F. F. Liu

California Institute of Technology
Pasadena, California
Attn: Professor F. T. Marble

Cornell Aeronautical Laboratory
Buffalo, New York
Attn: Dr. G. Markstein

Lockheed Aircraft Corporation
Missile Systems Division
Sunnyvale, California
Attn: Dr. W. Nachbar

Stanford Research Institute
Menlo Park, California
Attn: Dr. P. L. Nichols

University of Utah
Salt Lake City, Utah
Attn: Professor N. W. Ryan

Rohm and Haas Company
Redstone Arsenal
Huntsville, Alabama
Attn: Dr. H. M. Shuey

Rocketdyne
6633 Canoga Avenue
Canoga Park, California
Attn: Dr. R. Thompson

Armour Research Foundation
10 West 35th Street
Chicago, Illinois
Attn: Dr. T. P. Torda

Aeronutronic
Propulsion Department
Newport Beach, California
Attn: Dr. L. Green, Jr.

Aeronutronic
Propulsion Department
Newport Beach, California
Attn: Dr. H. Shanfield

Purdue University
Lafayette, Indiana
Attn: Professor M. J. Zucrow

Ultrasonics Laboratory
New York University
401 West 205th Street
New York 34, New York
Attn: Mr. Moshe Richman

Thiokol Chemical Corporation
Redstone Arsenal
Huntsville, Alabama
Attn: Dr. R. H. Wall

Thiokol Chemical Corporation
Reaction Motors Division
Denville, New Jersey
Attn: Dr. H. G. Wolfhard

Director of Research
AeroChem Research Laboratories, Inc.
Princeton, New Jersey
Attn: Dr. H. F. Calcote